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The influence of odd–even car trial on fine and coarse particles in Delhi☆

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A B S T R A C T

The odd-even car trial scheme, which reduced car traffic between 08.00 and 20.00 h daily, was applied from 1 to 15 January 2016 (winter scheme, WS) and 15–30 April 2016 (summer scheme, SS). The daily average $PM_{2.5}$ and PM_{10} exceeded national standards, with highest concentrations (313 μg m^{-3} and 639 μg m^{-3}, respectively) during winter and lowest (53 μg m^{-3} and 130 μg m^{-3}) during the monsoon (June–August). PM concentrations during the trials can be interpreted either as reduced or increased, depending on the periods used for comparison purposes. For example, hourly average net $PM_{2.5}$ and PM_{10} (after subtracting the baseline concentrations) reduced by up to 74% during the majority (after 1100 h) of trial hours compared with the corresponding hours during the *previous year*. Conversely, daily average $PM_{2.5}$ and PM_{10} were higher by up to 3–times during the trial periods when compared with the *pre–trial days*. A careful analysis of the data shows that the trials generated cleaner air for certain hours of the day but the persistence of overnight emissions from heavy goods vehicles into the morning odd–even hours (0800–1100 h) made them probably ineffective at this time. Any further trial will need to be planned very carefully if an effect due to traffic alone is to be differentiated from the larger effect caused by changes in meteorology and especially wind direction.

1. Introduction

The majority of cities worldwide are experiencing periods of elevated air pollution levels, which exceed international health–based air quality standards (CPCB, 2009; Kumar et al., 2013, 2016). Some of the highest air pollution levels are found in rapidly expanding cities such as Delhi in developing countries (Kumar et al., 2015). Exposure to high concentrations is linked to a broad spectrum of acute and chronic health effects in adults and children depending on the constituents of the pollutants (Heal et al., 2012; Rivas et al., 2017; Kumar et al., 2017). For example, WHO (2014) has reported ~7 million premature deaths worldwide due to indoor and outdoor air pollution in 2012. The developing countries of the Western Pacific and South East Asian regions bear most of this burden with 2.8 and 2.3 million deaths, respectively. In particular for Delhi, which is the focus of this article, increasing concentrations of particulate matter (PM) result in thousands of premature deaths and six million asthma attacks each year (Guttikunda and Goel, 2013). Recent work of Kesavachandran et al. (2015) reported that the outdoor exercisers in Delhi at locations with high $PM_{2.5}$ ($\leq$2.5 μm in aerodynamic diameter) concentrations are at a risk of lung function impairment due to their deposition in the smaller and larger airways.

Delhi and its National Capital Region (NCR) have a population of 25.8 million that is 7.6% of India's urban population. Of this, Delhi

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city alone has a population of 17.1 million, which has grown at a decadal growth rate of 47%. The total NCR area is 34,144 km^2, including Delhi city with an area of 1483 km^2 (Kumar et al., 2011). This drastic growth in population has resulted in extensive consumption of energy resource to meet their transportation and others demands (Kumar and Saroj, 2014). Studies are consistently showing high PM_{10} and $PM_{2.5}$ concentrations in the ambient air of Delhi, irrespective of the type of locations in Delhi city (Mandal et al., 2014; Pant et al., 2015; Sharma et al., 2013a; Tiwari et al., 2014). The adverse health impacts of high urban air pollution need to be managed to improve living standards but recent studies have ranked Delhi as the "worst" polluted city based on an environment performance index (Hsu and Zomer, 2014).

There were 6.93 million road vehicles in Delhi in 2011 and these are predicted to increase to 25.6 million by 2030 (Kumar et al., 2011). The current road length in Delhi city is 33,198 km with 864 signalised and 418 blinkers traffic intersections. The road network has increased from 28,508 km in 2000 to 33,198 km in 2015 while the number of vehicles has more than doubled from 3.37 million in 2000 to 8.83 million in 2015 (GoD, 2016; NCR, 2013). Delhi had 7.3 million road vehicles in 2015 compared with only 2 and 3.7 million in other megacities Mumbai and Chennai, respectively (Gupta, 2015). Interestingly, the traffic density per km of road is only 245 for Delhi compared with 1014 and 2093 for Mumbai and Chennai, respectively (Gupta, 2015; Kumar et al., 2015). This increase has resulted both in heavy traffic congestion and reduction in vehicular speed on the roads of Delhi, besides leading to increased emissions of pollutants such as $PM_{2.5}$, PM_{10} (≤ 10 μm) and NO_x (oxides of nitrogen) (CPCB, 2010; GoI, 2014). A brief summary of past studies between 1997 and 2016 is shown in Table 1, which indicates the concentrations of PM_{10} and $PM_{2.5}$ exceeding the national ambient air quality standards (CPCB, 2009). In Delhi city, CNG fuel was introduced for all public transport vehicles in 1998 (Chelani and Devotta, 2007). From 1998 to 2016, there has been an increase in CNG fuel operated public and private vehicles. Since the diesel and CNG-fuelled engines have a different operating configuration (Semin, 2008) there was no shift of diesel-fuelled to CNG-fuelled vehicles during the sampling period.

The Delhi traffic fleet is heterogeneous in nature in terms of fuels, engine capacity, technologies, vintage and mixed usage patterns that make pollution emission inventory estimation a challenging task. More than one–third of PM_{10} emissions in Delhi is generated by dust re-suspension (Guttikunda and Goel, 2013). Vehicle exhaust emissions are a major source of $PM_{2.5}$, contributing up to 45% of total $PM_{2.5}$ emissions in the Delhi NCR in the year 2010 (Kumar et al., 2016). Supplementary Information, SI, Table S1 summarises the findings of source apportionment studies carried out for Delhi city in the recent past.

The management of urban air pollution remains a major policy challenge in megacities like Delhi despite the implementation of several mitigation policies such as shifting of fuel used by public transportation from diesel to compressed natural gas, CNG (Dholakia et al., 2013), transforming coal power plants to natural gas (CPCB, 2010) and restriction on entry of heavy duty diesel vehicles in the city during the day time (Gulia et al., 2015a). Numerous kinds of schemes of road space rationing such as Rodízio or congestion pricing have been implemented in Latin America and European cities as a measure to alleviate the pollution levels. For example, Rodizio restricts each personal car for 1 day per week to run on the roads of Sao Paulo during 0700–1000 h (local time) and 1700–2000 h (Kumar et al., 2016; Rivasplata, 2013). Likewise, a short–term odd–even day trial was applied in Beijing during the 2008 Olympic Games (Cai and Xie, 2011). A number of studies have critically reviewed various stories of best practices of urban traffic management to reduce urban air pollution throughout the world (Dablanc et al., 2013; EEA, 2008; Gulia et al., 2015a). The results of these studies indicate reduced congestion due to such trials but there was no clear consensus about their impact on pollution levels.

The assessment and evaluation of benefits on ambient air pollution due to the implementation of policy measures such as odd–even trials are important but also challenging in a complex city like Delhi. In order to tackle the very high pollution levels in Delhi during winters, a 15 day odd–even car trial was applied by the Delhi Government between 1 and 15 January 2016 (winter scheme, WS), and the same between 15 and 30 April 2016 (summer scheme, SS), for personal diesel and petrol cars. The trial allowed an exemption to about 20 different categories such as cars driven by women, electric and hybrid cars, cars of very/very important persons, two–wheelers, emergency vehicles, ambulance, fire, hospital, prison, and enforcement vehicles. Personal light duty vehicles such as cars/jeep contribute ~40% of the total road traffic and are the dominant traffic fleet type in Delhi (Sharma et al., 2013b; Gulia et al., 2015b). The trial was applicable between 0800 and 2000 h (local time) during the weekdays and Saturday and allowed only private cars with their registration numbers ending with an odd number running on the road on odd dates of the month and those with even number allowed to run on even dates. The Delhi Government applied a fine of Rs. 2000 (about 30 U.S. dollar) for every violation of the odd–even car trial scheme in line with provisions of the Motor Vehicles Act 1988 to make this scheme successful. This resulted in a 15–20% reduction in traffic volume compared with the traffic volume before the odd-even scheme across the Delhi–Mathura Road, which is one of the most congested stretches in Delhi. Consequently, this resulted in a significant reduction of 30–50% of travel time during odd–even hours of the winter scheme compared with prior to the scheme. Furthermore, overall traffic volume reduced by ~19 and 17% on odd and even days, respectively, at Delhi–Mathura Road compared with that prior to the scheme. A reduction of about 24% in cars was noted during the odd and even days compared with those outside the scheme (Velmurugan and Gupta, 2016). There is no traffic count study available showing a reduction of traffic volume from roads across the whole of Delhi city during the odd–even schemes. While a reduction in traffic congestion on the roads of Delhi was reported during the trial days, there is no clear consensus whether the trial brought a reduction in the levels of PM_{10} and $PM_{2.5}$ concentrations. In this work, we comprehensively evaluate the data measured at the four monitoring stations across Delhi before and after the trial periods to understand the underlying factors affecting the concentration levels of PM during the trial days and the actual benefits brought by this scheme to reduce the levels of air pollutants.

2. Materials and methods

2.1. Study area

Delhi is located at an altitude of about 215 m above mean sea level and is one of the seventeen declared non–attainment areas in India (CPCB, 2006). Delhi experiences four major seasons across the year: summer (March–May), monsoon (June–August), post–monsoon (September–November) and winter (December–February). In summer, the city experiences dry weather with the temperature reaching up to 48 °C. The monsoon season experiences more than 80% of the total annual rainfall (Perrino et al., 2011). During winter, frequent ground–based inversion conditions occur with temperatures going down to 4 °C. These are winter months when the combination of inversion conditions coupled with emissions from paddy field burning upwind of Delhi (Kumar et al., 2015), together with biomass burning within Delhi itself for heating purposes (CPCB, 2006; Nagpure et al., 2015), bring almost

Table 1
A brief summary of relevant monitoring studies that have presented concentrations of different pollutants, including particulate matter, in Delhi.

Study period (location)	Pollutant considered	A brief summary of findings	Source
1997–1998 (Central Delhi, Roadside)	CO, NOx, SO, TSP	Annual average concentration of • CO (4810 ± 2287 & 5772 ± 2116 μg m^{-3} in 1997 and 1998, respectively) • NOx (83 ± 35 & 64 ± 22 μg m^{-3} in 1997 and 1998, respectively) • SO_2 (20 ± 8 and 23 ± 7 μg m^{-3} in 1997 and 1998, respectively) • TSP (409 ± 110 and 365 ± 100 μg m^{-3} in 1997 and 1998, respectively)	Aneja et al. (2001)
2001–2006 (Central Delhi, Roadside)	CO, NOx	• Influence of CNG fuel in Public transport (Auto and Buses) in Delhi city reduced • CO by 40% from 5000 μg m^{-3} (year 2002) to 3000 μg m^{-3} (year 2006) • NO_x increased by 50% from 63 μg m^{-3} (the year 2001) to 95 (the year 2004) followed by a slow decrease to 82 μg m^{-3} (the year 2006)	Kandlikar (2007)
2001–2008 (Overall Delhi mega city)	$PM_{2.5}$	• The observed concentrations are invariably • 40%–80% higher in the winter (November–January) and 10%–60% lower in the summer (May –July) • In summer $PM_{2.5}$ of ~60–90 μg m^{-3} • In winter $PM_{2.5}$ of ~200 μg m^{-3}	Guttikunda and Gurjar (2012)
2007–2008 (Central Delhi, Residential area)	PM_{10}, $PM_{2.5}$, PM_1	• The PM_{10}, $PM_{2.5,}$ and PM_1 concentrations were found to be 723, 588 and 536 μg m^{-3} during Deepawali days in 2007 • The PM_{10}, $PM_{2.5,}$ and PM_1 concentrations were found to be 501, 389 and 346 μg m^{-3} during Deepawali days in 2008. • PM_{10}, $PM_{2.5}$, and PM_1 levels in 2008 were 1.5-times lower than those in 2007	Tiwari et al. (2012)
2011 (Central Delhi, Residential area)	Black Carbon, $PM_{2.5}$	• Annual mean Black Carbon concentration was found to be 6.7 ± 5.7 μg m^{-3} • Annual mean $PM_{2.5}$ concentration was found to be ~122 ± 91 μg m^{-3}	Tiwari et al. (2013)
2010–2011 (Central Delhi, Residential area)	PM_{10} and $PM_{2.5}$	PM_{10} concentration • Winter = 335 ± 117 μg m^{-3} • Post monsoon = 316 ± 118 μg m^{-3} • Summer = 222 ± 77 μg m^{-3} • Monsoon = 89 ± 47 μg m^{-3} Daily $PM_{2.5}$ concentration • Winter = 221 ± 95 μg m^{-3} • Post monsoon = 200 ± 94 μg m^{-3} • Summer = 86 ± 27 μg m^{-3} • Monsoon = 59 ± 25 μg m^{-3}	Trivedi et al. (2014)
2013–2014 (Southwest Delhi, roadside location)	$PM_{2.5}$	12 h average $PM_{2.5}$ concentrations • Winter = 277 ± 100 μg m^{-3} • Summer = 58 ± 35 μg m^{-3} • Source of $PM_{2.5}$ were found different in winter and summer period.	Pant et al. (2015)

every year high pollution episodic conditions leading to frequent violation of air quality standards (CPCB, 2010; Pant et al., 2015). A recent study suggested that burning of biomass contributes approximately 26% and 17% of $PM_{2.5}$ and PM_{10} concentrations, respectively, in winter as well as 12% and 7% in summer in Delhi city, respectively (Sharma and Dikshit, 2016).

Delhi is surrounded by neighbouring cities of the National Capital Region (NCR; Fig. 1). The major neighbourhood cities are Sonepat in the north–west, Bahadurgarh, Jhajjar and Rohtak in west direction, Gurgaon and Manesar in the south, Faridabad in south–east, and Noida and Ghaziabad in the east. In Delhi city, a total of 19 monitoring stations are run by the Central Pollution Control Board, Delhi Pollution Control Committee (DPCC) and the Indian Institute of Tropical Meteorology Pune (under the SAFAR programme). Most of these stations monitor pollutants of regulatory interest such as PM_{10}, $PM_{2.5}$ SO_2, NO_x, and O_3.

2.2. Monitoring stations

As part of this work, we considered four air quality monitoring stations to evaluate the impact of the odd–even car trial on the concentrations of PM_{10} and $PM_{2.5}$ in Delhi city. The monitoring sites are selected in such a way so that they can cover a wide range of areas (i.e., industrial, commercial, residential and institutional) in Delhi city. Moreover, these stations provided us simultaneous data of both the PM_{10} and $PM_{2.5}$ for the periods considered in this study. NOx was not included in our analysis due to lack of parallel data for the considered periods and that it has multiple sources in Delhi, many of which such as local combustion for heating and cooking are poorly quantified. Of course, the availability of simultaneous data on pollutants and meteorology from additional monitoring stations would have further assisted to evaluate spatial effects of odd-even-trial at other locations in Delhi. The selected monitoring stations are located at Anand Vihar (AV, in the east of centre of Delhi), Mandir Marg (MM, centre of Delhi), Punjabi Bagh (PB, in the west of centre of Delhi and R. K. Puram (RKP, in the south of centre of Delhi) and all of them are operated by the DPCC. The AV station is located at the border of Delhi and Uttar Pradesh state. The surrounding area comprises a mixture of commercial, industrial and residential activities. It is located in the parking lot of an interstate bus transport depot and 150 m away from a heavy traffic road in the east district of Delhi, which has a population of 1,709,346 (Census, 2011). The MM station is located at one of the heavily trafficked kerbsides in New Delhi and surrounded by residential and commercial activities. The PB station is located 30 m away from the kerbside of an arterial road in West Delhi and surrounded by residential and commercial activities. The population of New and West Delhi is 1,42,004 and 2,543,243, respectively (Census, 2011). The RKP station is located away from the major road in South West Delhi and surrounded by residential activities. The population of south–west Delhi is 2,292,958 (Census, 2011). The detailed information of all the monitoring sites along with traffic volume on the nearest major roads are provided in SI Table S2.

2.3. Data collection

Continuous hourly average monitoring data for $PM_{2.5}$ and PM_{10} concentrations along with the meteorological parameters (relative

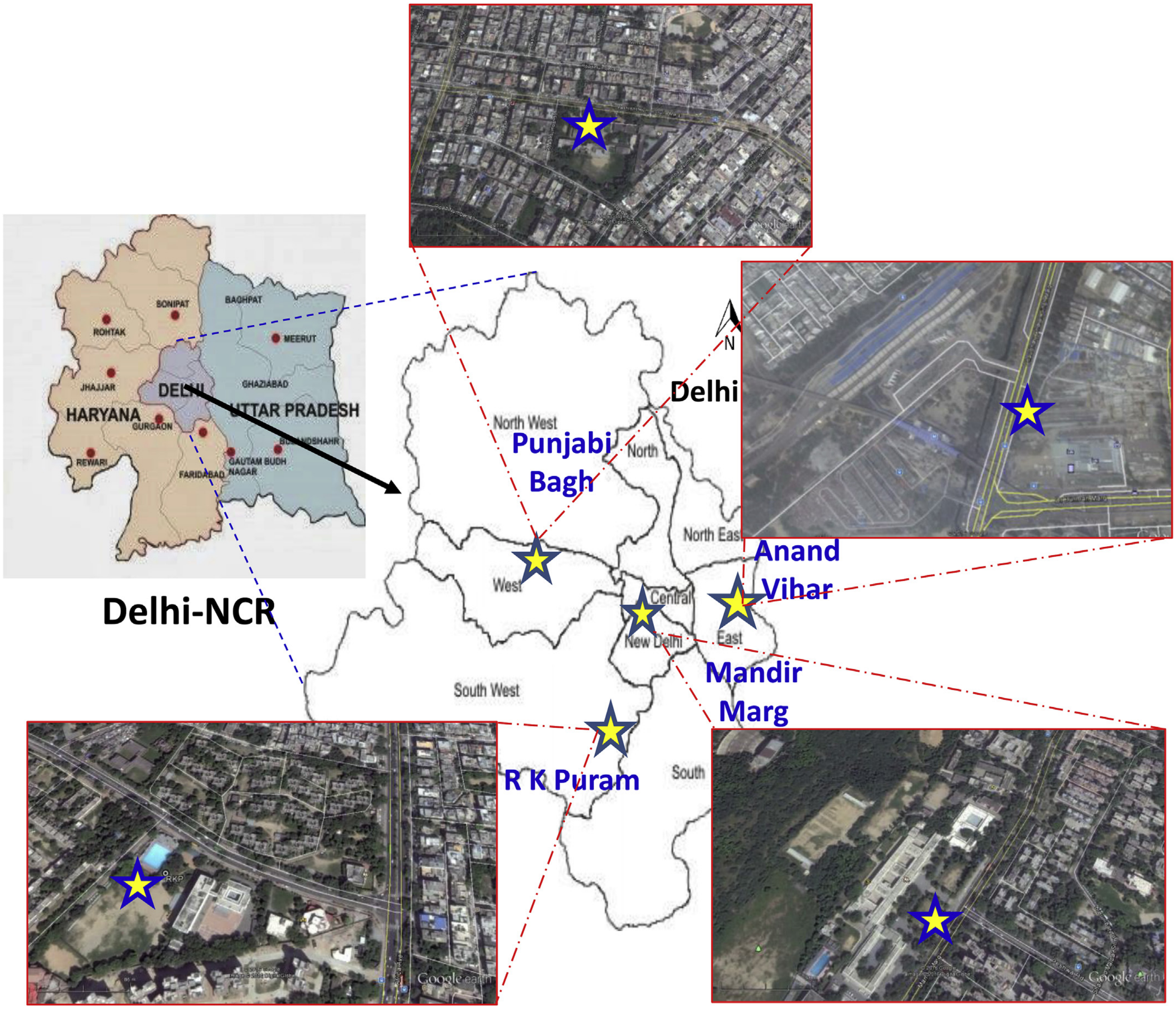

Fig. 1. The map showing Delhi–NCR region and location of monitoring sites (shown by yellow stars) in Delhi city. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

humidity, ambient temperature, wind speed, and direction) for all months of 2015, January 2016 and April 2016 was obtained from the selected four stations. Some missing hours were observed in the continuous times series data (Table 2), which were discarded from the analysis. The $PM_{2.5}$ and PM_{10} concentrations are monitored using BAM 1020 monitors, which work on the principle of beta attenuation (MOI, 2013); it is a USEPA recommended method and adopted by the DPCC (CPCB, 2011). The BAM analysers are calibrated for mass as well as undergoing flow rate checks on a weekly basis. The working principle and calibration details of the instrument are provided in SI Section S1. The hourly average meteorological parameters such as wind speed, direction, ambient temperature and relative humidity were collected from all the four stations (Section 2.2), which are operated by the DPCC. These instruments are calibrated every six months to ensure the quality of their data. The mixing height is one of the indicators of the atmospheric stability condition (Census, 2011; Perrino et al., 2011). The data for maximum atmospheric mixing height during each season in Delhi was taken from the Atlas of hourly mixing height and Assimilative capacity of atmosphere in India (MOI, 2013).

2.4. Statistical analysis

The hourly average concentration data were collected from the CPCB database for the study period of January–December 2015, 1–30 January 2016, and 1–30 April 2016. As summarised in Table 2, the selected periods provided a total of 10,224 h data for the analysis. The PM_{10} and $PM_{2.5}$ monitoring data capture was 80–84% at AV site, 81% at MM, 84–87% at PB, and 85–88% at RKP (Table 2). The meteorological data were available for 89–91% of the time at each site, except MM with 84% data. The data were analysed and compared in the form of diurnal and seasonal patterns, mean and standard deviations for each of the selected sites using the R program (Carslaw and Ropkins, 2012). In addition, bivariate polar plots

Table 2
Statistics of collected data for analysis; these numbers represent a number of data collected at each hour (AV, MM, PB, and RKP refer to Anand Vihar station, Mandir Marg station, Punjabi Bagh station and R.K. Puram station, respectively).

Locations	Monitoring parameters	$PM_{2.5}$	PM_{10}	RH	AT	WS	WD
AV	January–December 2015	7265	6851	7638	7638	7638	7635
	1–30 January 2016	713	693	716	716	716	716
	1–30 April 2016	657	615	702	702	702	702
	Total available data	8635	8159	9056	9056	9056	9053
	Data available (%age)	84%	80%	89%	89%	89%	89%
MM	January–December 2015	7082	7059	7347	7347	7347	7347
	1–30 January 2016	583	572	584	584	584	584
	1–30 April 2016	635	634	660	660	660	660
	Total available data	8300	8265	8591	8591	8591	8591
	Data available (%age)	81%	81%	84%	84%	84%	84%
PB	January–December 2015	7228	7446	7483	7624	7622	7551
	1–30 January 2016	710	714	725	725	725	720
	1–30 April 2016	666	686	627	708	708	708
	Total available data	8604	8846	8835	9057	9055	8979
	Data available (%age)	84%	87%	86%	89%	89%	88%
RKP	January–December 2015	7418	7589	7874	7874	7874	7874
	1–30 January 2016	691	700	720	720	720	720
	1–30 April 2016	580	700	719	719	719	719
	Total available data	8689	8989	9313	9313	9313	9313
	Data available (%age)	85%	88%	91%	91%	91%	91%

were drawn to assess qualitatively the effects of wind speed and direction on the measured concentrations for the full 2015 year, January 2016 (first odd–even car trial scheme during winter, referred hereafter as WS), and April 2016 (second trial during summer, SS). The concentrations are compared separately for odd–even (0800–2000 h) and non–odd–even (2000–0800 h) hours along with the corresponding hours of no odd–even trial year 2015.

3. Results and discussion

3.1. Diurnal behaviour of PM concentrations throughout the year

Table 3 presents a summary of $PM_{2.5}$ and PM_{10} concentrations at the selected air quality monitoring stations in Delhi. We divided the study duration into six different periods to investigate the variability in their concentration and for comparison with the odd–-even trial periods. These seasons included: (i) winter 1 (January–February 2015), (ii) summer (March–May 2015), (iii) monsoon (June–August 2015), (iv) post–monsoon (September–November 2015), (v) winter 2 (December 2015 – January 2016; this included the first odd–even winter scheme, WS), and (vi) summer 2 (April 2016, which included the second odd–even summer scheme, SS).

$PM_{2.5}$ at the AV station was found to be 222 ± 118, 134 ± 107, 89 ± 83, 133 ± 87, 313 ± 136 and 157 ± 127 μg m^{-3} for winter 1, summer 1, monsoon, post–monsoon, winter 2 and summer 2, respectively. As expected, $PM_{2.5}$ was highest during winter seasons, followed by summer and post–monsoon seasons, with the lowest being during the monsoon season. The higher $PM_{2.5}$ during winters is expected due to a relatively lower atmospheric mixing height (Supplementary Information, SI, Fig. S1), which inhibits the dispersion, compared with the other seasons (Tiwari et al., 2013). For example, the mixing heights (mean ± standard deviation) were about 2701 ± 261 m during summer, followed by 1741 ± 400 m during the post–monsoon, and only about 1107 ± 201 m during the winter (SI Section S2).

$PM_{2.5}$ was higher during winter 2 compared with winter 1. This trend was also shown by the rest of the monitoring stations (Table 3) and may be explained by the higher wind speeds (1.4 ± 1.0 m s^{-1}) during the winter 1 compared with 1.0 ± 0.7 m s^{-1} during winter 2 (SI Table S3). These observations suggest relatively better dispersion conditions during winter 1 than those during winter 2 to explain the differences observed in $PM_{2.5}$ concentrations. In the case of summer, $PM_{2.5}$ was higher during summer 1 compared with summer 2. This trend could be explained by both the relatively lower wind speeds and ambient temperature during the summer 1 (1.8 ± 1.2 m s^{-1} and 29 ± 8 °C) compared with summer 2 (1.9 ± 1.2 m s^{-1} and 33 ± 5 °C).

The PM_{10} at AV station was found to be highest during winter 2 (639 ± 241 μg m^{-3}), followed by post–monsoon (519 ± 260 μg m^{-3}), summer 1 (448 ± 308 μg m^{-3}), winter 1 (445 ± 218 μg m^{-3}), monsoon (329 ± 256 μg m^{-3}) and summer 2 (344 ± 215 μg m^{-3}) – this order changed from $PM_{2.5}$ which had highest for winter 2, followed by winter 1, summer 1, post–monsoon, summer 2 and monsoon. Similar trends of $PM_{2.5}$ and PM_{10} were also seen at the other three selected monitoring stations in Delhi city. This observation clearly confirms that PM_{10} and $PM_{2.5}$ in Delhi are affected substantially by the season (Pant et al., 2015). For example, high PM_{10} in the post–monsoon compared with winter 1 has an additional contribution from the burning of agricultural residue in the surrounding states of Punjab and Haryana that are located in a dominant upwind direction (Trivedi et al., 2014). Likewise, burning of firecrackers during the festival (e.g., Dussehra and Diwali) months of October to November creates extra contributions to both PM_{10} and $PM_{2.5}$ (Tiwari et al., 2013) while burning wood and cow dung cake for heating make additional contributions across winters (Kumar et al., 2015).

Besides the high seasonal variations, $PM_{2.5}$ and PM_{10} also showed large *diurnal* variations (SI Fig. S2). This analysis was particularly helpful to see the effects of odd–even hours on ambient concentrations. The concentrations were observed to be high during the morning peak hours (0900–1000 h), and night hours (2100–0500 h) when traffic volume is relatively low but the inflow of heavy goods vehicles through the city starts at 2200 h until 0800 h (Gulia et al., 2015a; Kumar et al., 2011). These are also the hours when the mixing height is low (SI Fig. S1) and winds are calm, resulting in weakened dispersion and hence the increased concentrations (Kumar et al., 2015; Tiwari et al., 2013). The effect of mixing height on the concentration was evident during the afternoon hours (1500–1700 h) when it was highest but both the $PM_{2.5}$ and PM_{10} were at their lowest (SI Fig. S2). As expected, there were

Table 3
Seasonal comparative assessment of $PM_{2.5}$ and PM_{10} in Delhi city; AV, MM, PB, and RKP refer to Anand Vihar, Mandir Marg, Punjabi Bagh and R.K. Puram sites, respectively, n = a total number of hourly observations over the period in the selected seasons.

Seasons	Parameter	AV		MM		PB		RKP	
		$PM_{2.5}$	PM_{10}	$PM_{2.5}$	PM_{10}	$PM_{2.5}$	PM_{10}	$PM_{2.5}$	PM_{10}
Winter 1 January–February 2015	n	1249	1206	1372	1375	1388	1378	1321	1381
	Mean	222	445	162	201	178	320	180	302
	STD	118	218	83	91	94	194	100	156
Summer 1 March–May 2015	n	1906	1828	1710	1718	1979	1970	2114	2149
	Mean	134	448	72	191	96	238	92	225
	STD	107	308	45	142	67	169	60	159
Monsoon June–August 2015	n	2024	1836	1995	1967	1847	2055	2040	2075
	Mean	89	329	53	130	73	148	68	140
	STD	83	256	53	107	54	114	56	124
Post–monsoon, September – November 2015	n	1404	1341	1345	1342	1323	1332	1338	1260
	Mean	133	519	78	152	101	220	101	228
	STD	87	260	50	67	63	111	62	125
Winter 2 December 15–February 2016	n	2083	1870	1946	1943	2088	2147	2014	2155
	Mean	313	639	216	358	260	460	261	437
	STD	136	241	95	140	116	195	129	185
Summer 2 March–May 2016	n	460	455	405	417	429	371	552	545
	Mean	157	344	70	239	95	282	133	310
	STD	127	215	47	110	74	131	80	158

no clear hourly peaks during the monsoon season, mainly due to the frequent occurrence of rain (SI Fig. S2).

3.2. PM concentrations in pre–, during and post odd–even trial periods

Bivariate concentration polar plots for $PM_{2.5}$ (SI Fig. S3) and PM_{10} (SI Fig. S4) were drawn to understand the location and characteristics of different sources affecting each of the selected locations. For better visualisation and quick directional information on sources, adjacent bins with the mean concentration values have been modified by using the smoothing technique (Azarmi et al., 2015; Carslaw and Ropkins, 2012; Mouzourides et al., 2015). Therefore, the colour bars should not be interpreted as actual measurement values.

The $PM_{2.5}$ pattern was found to be different at all the studied locations throughout the years 2015 and 2016. For example, irrespective of wind speed, high concentrations were observed at AV when the wind direction was west–southwest. This could be primarily due to a contribution from a nearby bus depot that is ~120 m in the upwind south–west direction of the station (SI Figs. S3a–c). However, this pattern changed during the summer compared with the winter season. For example, in April 2015, $PM_{2.5}$ concentration peaks were observed when the wind direction was east–northeast during the summer months with an average wind speed of ~2 m s^{-1} (April 2015; SI Fig. S3d). On the other hand, predominant winds were from south–west and north–west with an average wind speed of about 2–3 m s^{-1} during April 2016 (SI Fig. S3e). Likewise, in January 2015 and January 2016, $PM_{2.5}$ concentration peaks were observed when the wind direction was south–west with average wind speeds of 2.2 m s^{-1} and 1.5 m s^{-1}, respectively. In addition, peaks were also observed when the wind direction was east–northeast with a wind speed of ~4 m s^{-1} during January 2015 and east–southeast with average wind speed of 1–2 m s^{-1} during January 2016. We carried out a similar analysis for the remaining sites (MM, PB, and RKP), which is presented in SI Section S3, to understand whether the direct comparison of the odd–even periods with the preceding years would clearly reflect its effect on PM types. All these observations clearly indicate that the comparison of the odd–even trial period in January 2016 or April 2016, compared with the corresponding period in 2015 or 2016, will be affected by the different background concentrations, and therefore a difference in $PM_{2.5}$ (or PM_{10}) concentrations between these two months cannot be taken as a direct result of the odd–even trial periods in January and April 2016. Therefore as a necessary step, we estimated the baseline (local site background) concentrations at our selected sites.

3.2.1. Estimation of baseline PM concentrations at sites

Given the discussions above where difference in wind directions and wind speed makes it challenging to make a direct comparison of odd–even trial periods in 2015 and 2016, it is important to estimate the background concentrations of PM at each site so that these values could be deducted from the time series during the comparison (Section 3.3). We adopted the same approach, as used in our previous work (Hudda et al., 2014; Goel and Kumar, 2015), to estimate the baseline background concentrations as the lowest 5th percentile of the observed hourly $PM_{2.5}$ and PM_{10} data (SI Table S4). The use of the lowest 5th percentile values of time series for estimation of baseline PM concentrations excludes the micro- and middle-scale impacts due to local sources, usually vehicles (Hudda et al., 2014; Goel and Kumar, 2016). These studies applied the 5th percentile value of the time series of PM concentrations and found that the baseline concentrations were relatively spatially uniform outside of the study impact areas, with a coefficient of variation being less than 5%. The baseline background concentrations of $PM_{2.5}$ at the AV station were estimated to be higher during the WS (113 μg m^{-3}) and SS (33 μg m^{-3}) compared with the corresponding values of 69 and 26 μg m^{-3} during 2015. Likewise, PM_{10} was found to be higher during WS (252 μg m^{-3}) and SS (81 μg m^{-3}) compared with the corresponding values of 103 and 60 μg m^{-3}, respectively, during 2015. Similar estimates were made for the other stations, as explained in SI Section S4, and the following trends were observed. Firstly, the baseline concentrations of $PM_{2.5}$ and PM_{10} were always higher by 2.6–7.4 and 1.0–3.1 times, respectively, during the WS compared with SS. Secondly, the baseline concentrations for $PM_{2.5}$ (and PM_{10}) were higher by 1.1–1.7 (1.8–2.5) and 0.8–3.4 (1.4–3.1) times higher, respectively, in 2016 compared with the corresponding months in 2015. The above observations suggest that each site received different baseline concentrations during the odd–even car trial phases compared with the same months in a preceding year. The fact that the baseline concentrations of both

$PM_{2.5}$ and PM_{10} are large and affected by season, clearly suggests that the interventions such as odd–even trials will not be effective to cut down the overall concentrations unless measures to control the baseline concentrations from the inner (e.g., roadside biomass burning, construction and resuspension of road dust; Kumar et al., 2015) and peripheral sources (e.g., brick kilns, burning of agriculture residue, industrial emissions and biomass burning for cooking and heating; Nagpure et al., 2015) contributing to PM in Delhi are also controlled.

3.3. Odd–even trial impact on PM concentrations

In order to better understand the actual impact of odd–even car trial schemes, the diurnal variations of total and net (Δ) $PM_{2.5}$ (Fig. 2) and PM_{10} (Fig. 3) concentration were plotted for the WS and SS (SI Figs. S5–S6) in 2016 and compared with diurnal plots of 1–15 January 2015 and 15–30 April 2015. The net concentrations are essentially the total concentrations minus the baseline concentrations at each site, which differ during seasons and between sites (Section 3.2), and therefore need to be subtracted to see the real impact of the reduced car fleet during the odd–even trial period. These figures were further divided into odd–even (0800–2000 h) and non–odd–even (2000–0800 h) hours to visualise their temporal trend at each site. Polar concentration roses of $\Delta PM_{2.5}$ (SI Fig. S7) and ΔPM_{10} (SI Fig. S7) after subtracting the baseline concentrations were drawn to understand the direction of major road traffic affecting each of the selected locations.

3.3.1. Winter trial

During the *WS* (1–15 January 2016), $\Delta PM_{2.5}$ was found to be relatively low during the odd–even hours (1100–2000 h) and high during non–odd–even hour (2000–0800 h) when compared with the corresponding hours of the previous year of 2015 (SI Section S5). For example, $\Delta PM_{2.5}$ across all the sites ranged from −2 to −44% during odd–even hours, but were higher by 2–127% (0700–0800 h at MM site) during non–odd–even, hours compared with the corresponding values of the previous year (SI Section S6). This effect was the lowest (−2%) and the highest (−44%) at MM and RKP, respectively. Furthermore, hourly averaged $\Delta PM_{2.5}$ across all the sites was found to be higher during early odd–even hours (i.e., 0800–1100 h) compared with the corresponding values of last year. For example, $\Delta PM_{2.5}$ was higher by 9–83%, 17–99%, 7–88% and 6–91% during these hours at AV, MM, PB and RKP, respectively, compared with the corresponding values of the previous year (SI Sections S6-S7). It is clear from the above observations that the fine particles were reduced during the majority of hours, except early odd–even hours (0800–1100 h), compared with the corresponding previous year's concentration. This trend indicates the persistence of overnight emissions into the early morning due to a lag effect. On the other hand, such a reduction was non–existent during the non–odd–even hours when the concentrations were found to increase by up to 127% against the corresponding values of last year. Therefore, odd-even car trial schemes appears to help in reduction of ambient $PM_{2.5}$ and PM_{10} despite an annual growth in traffic volume of ~7% in winter 2 compared with winter 1 (Goel et al., 2015). No special circumstances were noted between the two periods, which would have affected the emission from the other sources such as industrial activities and roadside open biomass burning (Kumar et al., 2015). Similar to $PM_{2.5}$, PM_{10} also showed the identical daily trend during the WS and SS. For example, ΔPM_{10} across all the sites during the *WS* ranged from −5 to −49% during the majority of odd–even hours (1100–2000 h), but was higher by 5–157% during non–odd–even hours (2000–0800 h) compared with the corresponding values of the previous year (SI Section S8). Similar to $\Delta PM_{2.5,}$ ΔPM_{10} was found to be higher by 26–145%

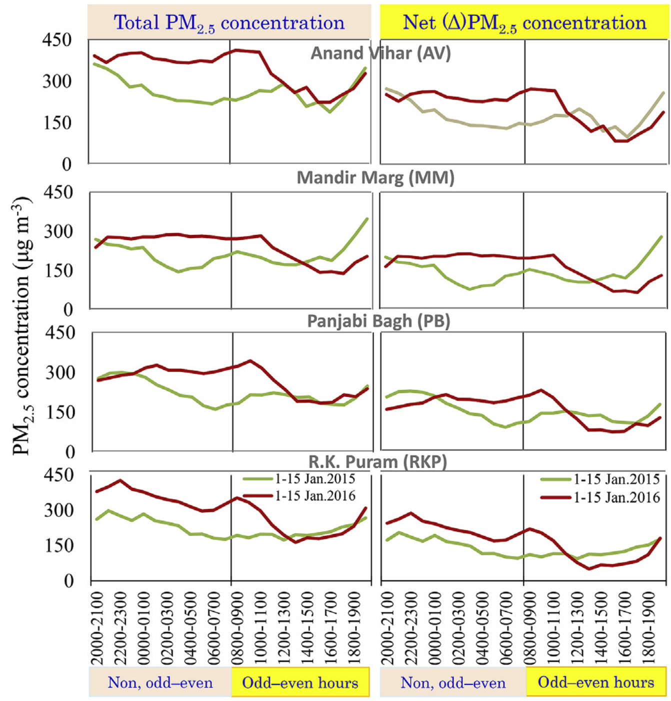

Fig. 2. Diurnal variation of total and net (shown by Δ are the concentrations after subtracting background concentrations) $PM_{2.5}$ for January 2015 and 2016 during odd–even days.

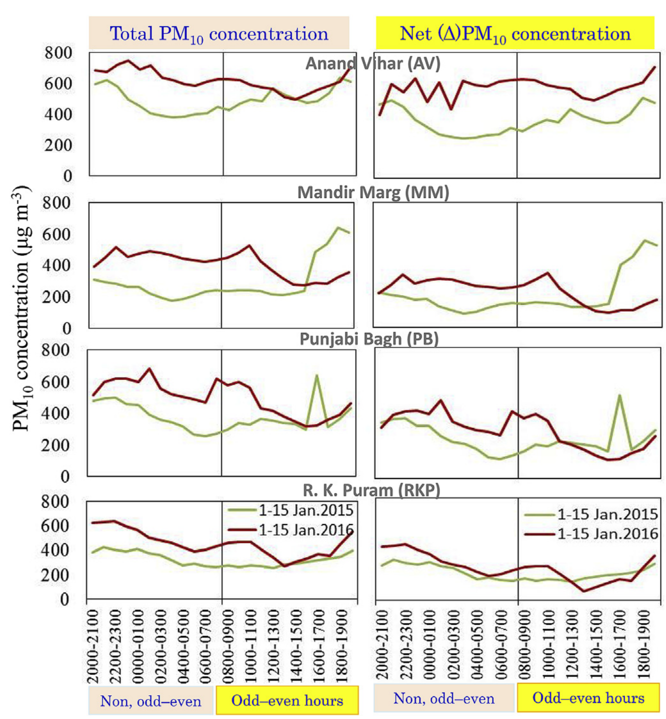

Fig. 3. Diurnal variation of total and net (shown by Δ are the concentrations after subtracting background concentrations) PM_{10} for January 2015 and 2016 during odd–even days. Please note that the legend is common for all the sub-figures and red lines represent data for the year 2016. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

during the early morning odd–even hours (0800–1100 h) compared with the corresponding values of the previous year (Fig. 3).

Congestion and road user charging schemes have been implemented successfully in cities such as London with an aim to reduce traffic count on roads in specially defined zones. This scheme reduced CO_2, NO_x and PM_{10} emissions by ~16, 13 and 7%, respectively, in the year 2003 compared with prior to scheme implementation in the previous year (EEA, 2008). In another study, Hasheminassab et al. (2014) found a decrease by 24 and 21% in $PM_{2.5}$ emissions from the year 2008–2012 in Los Angeles and Rubidoux, respectively, compared with the corresponding values in the year 2007 due to implementations of stringent emission standards. Our above observations clearly indicate that the odd–even trials appear to have generated cleaner air for certain hours of the day compared with the corresponding values of the previous year. However, the persistence of overnight emissions from the heavy goods vehicles into the early morning hours points to a need for tighter control on the entry of these vehicles during the early morning hours when the atmospheric conditions are the least favourable for mixing of the emitted pollutants. For example, a survey by CSE (2015) provides evidence of a substantial number of vehicles entering and exiting the Delhi city. This survey included the period of 20:00 h to 08:00 h and nine different points. The survey reported that the about 85,799 light and heavy goods vehicles enter and exit from all the studied points. During the day time, entry of commercial vehicles in the Delhi city is banned.

3.3.2. Summer trial

During the *SS* (15–30 April 2016), $\Delta PM_{2.5}$ were also found to be relatively low during the afternoon odd–even hours (1200–2000h) and high during non–odd–even hours (2000–0800 h) when compared with the corresponding hours of the previous year (SI Fig. S5). For example, $\Delta PM_{2.5}$ across all the sites fell by −1 to −74% during these odd–even hours, but was higher by 1–82% during non–odd–even hours compared with the corresponding values of the previous year (SI Section S6). The smallest (−1%) and the largest (−74%) values were seen at AV and PB, respectively. Similar to WS, hourly averaged $\Delta PM_{2.5}$ was found to be higher by 35–176%, 2–33%, 56–135% and 57–73% during early odd–even hours (0800–1200 h) at AV, MM, PB and RKP sites, respectively, compared with the corresponding values of the previous year. Likewise, $\Delta PM_{2.5}$ was higher by 16–128%, 5–82%, 6–34% and 1–49% during non–odd–even hours at AV, MM, PB and RKP, respectively, compared with the corresponding values of the previous year (SI Section S6). The above observations suggest a change between −1% and −74% during the afternoon odd–even hours while such an effect was non–existent during morning odd–even and non–odd–even hours – as was observed during the WS.

A similar trend was observed for Δ PM_{10}. For example, ΔPM_{10} across all the sites during the *SS* ranged from −1 to −63% during the majority of odd–even hours (1300–2000 h), but was higher by 1–43% during non–odd–even hours (2000–0800 h) compared with the corresponding values of the previous year (SI Section S3). Similar to $\Delta PM_{2.5}$, ΔPM_{10} was found to be higher by 4–81% during the early morning odd–even hours (0800–1200 h) compared with the corresponding values of the previous year (SI Fig. S6).

3.4. Trend in PM against the preceding trial periods

In order to assess further the trends in PM concentrations during both the schemes against the preceding period at all the sampling sites, we adopted two approaches to choose daily average $PM_{2.5}$ and PM_{10} as reference values for comparison. The first approach included the daily average values of 25 December 2015 and 1 April 2016 as reference values for the WS and SS, respectively. In the second approach, we matched days with meteorological parameters (i.e., wind speed, wind direction, ambient temperature and relative humidity) during the year 2015 which were very similar to those during the odd–even trial periods (SI Table S5). This matching was performed by sorting the daily average data between ranges of minimum and maximum values at the respective sites. The number of days matched with the odd-even data at different sites during both the WS and SS are shown in SI Table S5. The daily averaged reference values of $PM_{2.5}$ and PM_{10} were then estimated for comparison with the odd–even trials for both the WS and SS at all the studied locations.

Both the approaches provided a comparable trend. For example, Figs. 4 and 5 show the variations in $PM_{2.5}$ and PM_{10} against daily average reference values of 25 December 2015 and 1 April 2016 during the WS and SS (SI Figs. S9–S10), respectively. Both the $PM_{2.5}$ and PM_{10} during the WS in 2016 showed a similar trend. For example, the concentrations were usually higher (except on 9 and 15 January 2016) against the reference value, reaching up to ~3–times in 2016 compared with a reduction by up to half in 2015, compared with the reference value. These observations point to three key conclusions: (i) PM concentrations during the odd–even trial were usually higher compared with the preceding days of the odd–even trial in 2016, (ii) PM concentrations during 2015 were always lower reaching half of reference values on certain days in January 2015, and (iii) PM concentrations during WS were usually higher than those of the pre–trial period. As for the SS, $PM_{2.5}$ (SI Fig. S9) and PM_{10} (SI Fig. S10) showed relatively unchanged concentrations at most stations, except MM, against the reference value (daily average 1 April 2016) during both the months of April 2015 and April 2016. This indicated that the PM concentrations during SS did not change much during the odd–even period compared with a reference value for the pre–trial period. Likewise, $PM_{2.5}$ and PM_{10} during WS and SS, when compared with their reference concentrations that were estimated using the second approach, showed a usual increase during WS (SI Figs. S11–S12), except a decrease during SS (SI Figs. S13–S14) on some occasions on the odd–even days.

Combining the results of Sections 3.3 and 3.4 allows presentation of the trends in contrasting ways as to whether the odd–even trials reduced or increased concentrations of PM. For example, if the PM concentrations during the odd–even hours are compared against the previous year's concentrations there has clearly been a decrease in concentrations (Section 3.3). However, concentrations of PM were found to increase during the odd–even hours if the reference value for comparison is taken as the days before the pre–trial period (SI Figs. S9 and S10).

4. Conclusions and future outlook

This study has evaluated the impacts of two recently implemented odd–even car trials during winter (WS; 1–15 January 2016) and summer (SS; 15–30 April 2016) in Delhi on the reduction of ambient PM_{10} and $PM_{2.5}$ concentrations. The data for $PM_{2.5}$ and PM_{10}, together with the local meteorological parameters, for the 2015 and 2016 years were analysed with an aim to quantify the influence on $PM_{2.5}$ and PM_{10} due to the implementation of odd––even trial schemes during the two seasons.

The following conclusions were drawn

- A huge variability in both $PM_{2.5}$ and PM_{10} concentrations was found among the sites and seasons within Delhi. For example, the average $PM_{2.5}$ ranged within a factor of ~6 with a minimum value of 53 $\mu g\ m^{-3}$ (at site MM during monsoon) to a maximum value of 312 $\mu g\ m^{-3}$ (at site AV during winter). Likewise, the

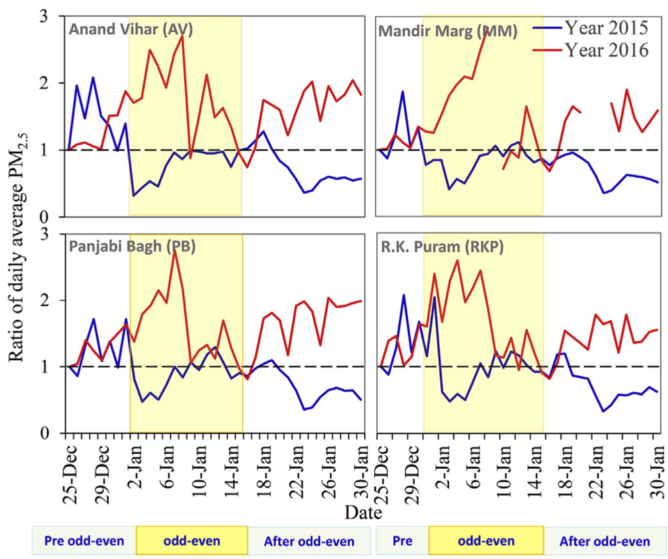

Fig. 4. Daily change in relative concentrations of $PM_{2.5}$ against the daily average concentration on 25 December 2015. The broken line for MM shows a missing data set. Please note that the legend is common for all the sub-figures and red lines represent data for the year 2016. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

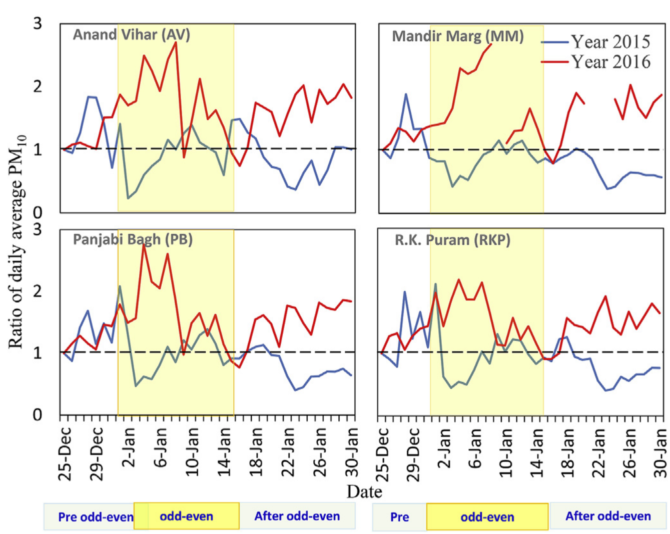

Fig. 5. Daily change in relative concentrations of PM_{10} against the daily average concentration on 25 December 2015. The broken line for MM shows a missing data set.

average PM_{10} ranged within a factor of ~5 with the lowest and highest values of 129 μg m^{-3} (at site MM during monsoon) and 639 μg m^{-3} (at site AV during winter), respectively. These observations clearly showed a high variability in PM concentrations, with $PM_{2.5}$ showing a little higher variability compared with PM_{10}. Furthermore, the highest concentrations in both PM types were always during winter when both the meteorological conditions and emissions appears to be the key factors to drive ambient air quality and the lowest always during a monsoon season, mainly due to limited dispersion and precipitation, respectively.

- The baseline concentrations of both $PM_{2.5}$ and PM_{10} varied hugely between the selected sites and therefore were used to assess the net effect of odd−even trials on the ambient concentrations. For example, the baseline $PM_{2.5}$ was found to be lowest and highest at 12 and 113 μg m^{-3} at RKP and MM stations, respectively. It indicates that the baseline concentrations of $PM_{2.5}$ itself are 0.5− to 4.5−times higher than the mean 24 h WHO limit value of 25 μg m^{-3}. Likewise, the baseline PM_{10} was found to be the lowest and highest as 31 and 252 μg m^{-3} at site RKP and MM, respectively. The corresponding baseline concentrations of PM_{10} itself were 0.6− to 5.0−times higher than the mean 24 h WHO limit value of 50 μg m^{-3}. These observations clearly suggest controlling the baseline concentrations as a basic step towards improved air quality, as also discussed in our recent work (Kumar et al., 2013, 2015).
- During the WS and SS trial periods, $\Delta PM_{2.5}$ and ΔPM_{10} were found to decrease during the odd−even periods, but these were higher during the morning odd−even and the rest of the non−odd−even hours compared with the corresponding period during the previous year. This seems likely to be related to the time taken for dispersion of the pollutants emitted overnight. The effect of the odd−even hours during the WS ranged from a minimal reduction of −2% to a maximum reduction of −44% during peak traffic hours across the studied sites; this effect was relatively larger during the SS with the corresponding reduction of −2% to −74% estimated.
- ΔPM_{10} followed the same trend as the $\Delta PM_{2.5}$. The effect of the odd−even period during the WS ranged from a minimal reduction of −5% to a maximum reduction of −49% during peak traffic hours across the studied stations compared with the corresponding period during the last year. This effect was relatively larger during the SS when the corresponding reduction of −1% to −63% was noted.
- While the monsoon season showed the lowest ambient PM concentrations, the higher mixing height during summer assists in better mixing to reduce ambient PM concentrations. The winter episodic conditions are due to a low mixing height and are most likely exacerbated by the emissions from heavy goods vehicles during night time when the mixing height was lowest. Any traffic taken from the road during the odd−even trial will assist in reducing concentrations during the certain peak exposure times (early morning and late evening hours). However, the real gains can only be achieved by restricting the entry of heavy goods vehicles during night hours. These vehicles contribute up to 65% of total particle numbers (Kumar et al., 2011) and nearly half of the PM_{10} emissions from the exhaust of on-road vehicles in Delhi (Jain et al., 2016; Nagpure et al., 2016) and a likely reason to build up background concentrations during the night hours.

This work analysed the data available from the fixed−site monitoring stations to assess the effect of the odd−even trial on the PM concentrations. While a clear picture emerged from the analysis of odd−even trial efforts, further studies are recommended to target background measurements under different meteorological conditions and seasons. The monitoring of on−road traffic volume before, during, and after the odd−even trial periods through control studies in future could also help in determining the actual reduction in different types of on-road vehicles and their emissions. Furthermore, mobile monitoring around such interventions could provide better spatial resolution of concentrations and identify pollution hotspots within the city to prioritise specific emission control strategies. From the use of routine air quality data, it has not been possible to differentiate clearly the changes in air quality attributable to changes in road traffic from those due to other sources of emissions. It is recommended that before such a trial is next implemented, measures are put in place to enable either full source apportionment of the particulate matter, or as a minimum, measurement of chemical tracers for road traffic emissions.

Moreover, very careful planning of the study, including simultaneous data for air pollution, meteorology and vehicle count during such periods of interventions, will be needed if it is to differentiate between the effects of changes in emissions and meteorology upon the measured concentrations.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.envpol.2017.03.017.

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